DRIVEN SUBCRITICAL FISSION RESEARCH REACTOR USING A CYLINDRICAL INERTIAL ELECTROSTATIC CONFINEMENT NEUTRON SOURCE

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1. Introduction

An accelerator-driven sub-critical reactor potentially offers important safety advantages for future fission power systems [1- 5]. A fast neutron spectrum sub-critical reactor system with heavy metal coolant has received considerable attention in Europe and in the US and Japan. Alternate versions, using intermediate or thermal spectrum neutronics with lighter moderators are also possible. Another attractive application of a driven reactor is for burning of plutonium isotopes, actinides and select long-lived fission products. In addition to large power reactors, special low power designs are candidates for student subcritical laboratory experiments and research reactors. The driven system is especially beneficial since the enhanced safety allows a wider variety of experimental conditions, including dynamic studies.

The main approach considered for the driver to date has been an accelerator, spallation-target system. While this concept appears to be feasible, the large size and cost of the accelerator system remain an issue. Also, the in-core target system poses significant design and engineering complications. Here we consider the alternative of using a unique inertial electrostatic confinement (IEC) neutron sources which are small enough to fit within fuel element channels or in a central cavity region of the sub-critical core assembly. Thus, the IEC replaces both the accelerator system and spallation target by either a central neutron source or by multiple modular sources configured as elements within the “standard” core assembly. This provides flexibility in design of the core and in flux profile control. Most importantly, these small units can be produced at a lower cost than the accelerator-target system.

Considerable research on the IEC concept has already been carried out on a laboratory scale [6-10]. However, a key remaining issue concerns the ability to achieve the high neutron rates required using the small volume units that are envisioned. Also, there are engineering issues such as the high-voltage feed-throughs, which will require improved technology to prevent unwanted arcing in the intense radiation fields encountered in the reactor core. Ongoing IEC research aimed at the higher neutron yields required is described here.

2. Prior Work on the IEC Neutron Source

The basic IEC concept traces back to Philo Farnsworth, the inventor of electronic television. The present IEC neutron source units are a modification of his original design which developed a unique grid-produced plasma discharge, operating in the unique “star” mode [11]. This configuration is illustrated conceptually in Figure 1. The ion gun added is not used in the “base” gridded star mode design. In addition to the spherical unit, a unique cylindrical version has also been developed at the University of Illinois and it provides an alternative geometry for sub-critical driven application.

In the spherical design the transparent grid, biased at 60 to 100-kV, acts as a cathode relative to the grounded vacuum vessel wall. When deuterium is used, ions produced in the discharge are extracted from the plasma by the cathode grid, accelerated, and focused at the center of the sphere where nuclear fusion reactions occur. The grid provides recirculation of the ions, increasing the power efficiency. At high currents, an electric potential structure develops in the non-neutral plasma, creating virtual electrodes that greatly enhance ion containment and recirculation [11, 12]. This feature is essential for the

good ion confinement required to develop efficient, high neutron yield devices. Once formed, the virtual electrodes replace the grids which can then be removed. Experimental measurements have demonstrated the existence of such potential structures, but at considerably lower currents than those required for higher yields. Structure stability could be an issue at high currents, although theoretical studies have not identified a problem to date.

Present steady-state IEC units produce ~10^8 D-D n/s, while advanced pulsed versions extend to 10^{10} n/s, equivalent to 10^{12} n/s if DT is used under similar conditions. As discussed later, this is in the range desired for use in small research reactors, but roughly four orders of magnitude lower than needed for driven power reactor applications. Still, the present devices have greatly enhanced the understanding of the discharge physics involved and, from a practical viewpoint offer an attractive low-level neutron source for applications such as a neutron activation analysis (NAA) [13].

The concept of using an IEC to drive a sub-critical reactor was proposed earlier based on gridded IEC concepts [6-10]. However, grid transparency issues can be avoided by the use of virtual electrode structure formed in a high current ion-injected spherical IEC or, alternatively in the hollow electrodes cylindrical IEC design [14, 15]. Both approaches are briefly discussed here.

3. Ion Injected IECs

Recent IEC research at the UIUC has explored a unique external ion source, ILLIBS (Illinois Ion Beam Source) as a way to ultimately achieve virtual electrode IEC operation. ILLIBS employs a RF-driven plasma in a graded magnetic field configuration (see Fig. 2), and can be incorporated into the IEC as shown in Fig. 1. This allows initiation of the plasma discharge below the normal (Paschen relation) discharge break-down region, and due to the low chamber pressure losses due to charge exchange are greatly reduced, improving the neutron production efficiency and allowing higher yields. Wide ranges of sub-breakdown deuterium pressures (0.4 to 2 mTorr) have been studied. With 100 Watt input RF power, ILLIBS provides a high ion current extraction efficiency and a deuterium ion flux of 6 x 10^{18} ions/(cm^2-sec) at 65 mA with a well collimated beam diameter of ~3 mm. With the ion gun on, a neutron rate of 2 x 10^7 n/sec was achieved with grid voltage and current at 75 kV and 15 mA respectively, at 1.2 mTorr. These results suggest that using the D-T gas mixture and increasing the ion current in this unit, would give a neutron rate of 7.3 x 10^{12} n/sec at 1.2 mTorr, 75 kV and 1.5-A ion current. This would provide neutron levels consistent with low power research reactor requirements discussed later. Such operation provides a significant improvement in neutron production efficiency, reducing power handing problems associated with high yield operation. Significantly higher yields could be achieved by further increasing the input power and adding multiple ILLIBS units.

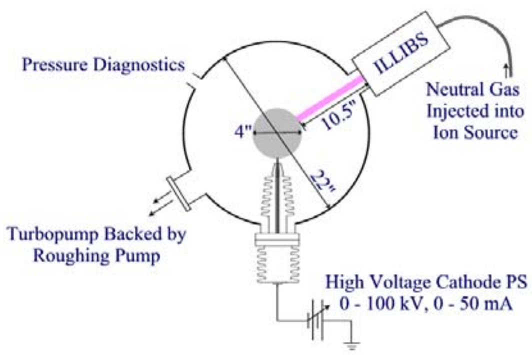

Figure 1. Arrangement of the gridded star mode IEC with the ILLIBS ion source

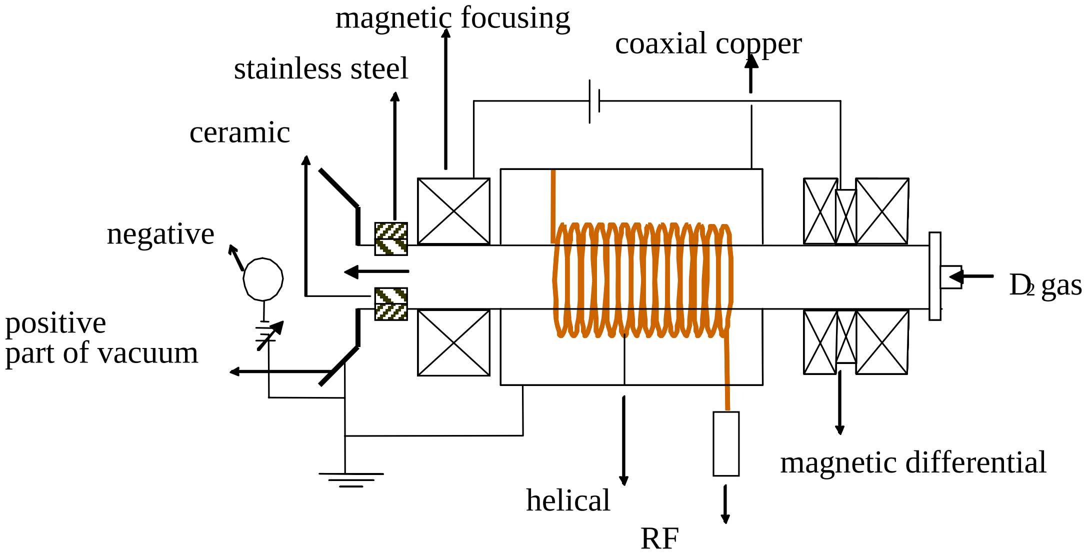

Figure 2. Typical setup of the ILLIBS. The main components are: magnetic-index dc coils, coaxial cooper shielding, antenna, front magnetic focus coil, and floating exit nozzle. The three back coils are connected in series.

The details of ILLIBS are shown in Figure 2. The antenna is made from ~ 4 meters length of coaxial insulator high voltage wire, wound around a glass tube containing the fill gas. The RF signal (13.56 MHz) is applied to one end of the antenna while the other end is grounded. The oscillating magnetic field created within the coil is directed along its axis and induces a vortex electric field. Then, the negative potential on the IEC grid serves to extract ions from the RF discharge.

4. Cylindrical IECs

While most IEC research to date has involved spherical devices, cylindrical IECs offer many advantages in a variety of practical applications, including the present sub-critical reactor system [14, 15]. The cylindrical geometry is advantageous in a wide range of engineering configurations that require coverage of a broad area with neutrons. It is also capable of more efficient heat rejection than the gridded spherical unit, since rejected heat is carried by the larger area hollow electrodes vs. thin-line or plates.

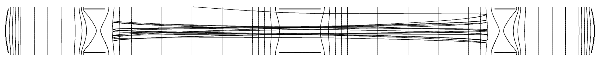

Figure 3 Diagram of the C-device with calculated ion trajectories and equi-potential surfaces

The prototype cylindrical IEC version (Figure 3), called a C-device, has a geometry that is particularly attractive for the driven sub-critical application. It forms deuterium (or deuterium-tritium) beams in a hollow cathode configuration such that fusion occurs along the extended colliding beam volume in the center of the device, giving a line-type neutron source. The prototype design uses hollow cylindrical anodes (held at ground potential) at either end of the unit, while a similar, but longer hollow cylindrical cathode in the center of the device is biased to a high negative potential. Deuterium gas introduced at the end of the unit is ionized in the resulting discharge, creating an ion source. These ions are accelerated back and forth along the axis of the unit, where they collide and fuse.

The prototype C-device shown in Figure 1, uses three electrodes placed in a cylindrical glass vacuum chamber having a diameter of ~8 cm and length of ~100 cm. The center cathode is constructed from a hollow, thin-wall, stainless steel tube. The two anodes are also hollow steel tubes, held at a large positive potential (about +80kV). Positive ions formed in the plasma between the electrodes are accelerated toward the center cathode. Because the anodes and cathode are hollow, most ions and electrons pass through them without colliding with the structure, giving an effective transparency of ~100%.

Figure 4 also shows a calculated ion trajectory plot for the C-device. The tightly focused beams passing through the center cathode are evident from the plot. The electrodes at the ends of the chamber, called

"reflector" dishes, are solid, concave steel surfaces held at ground potential. These dishes "reflect" and focus electrons toward the center of the anodes where they pass through and recirculate in a manner similar to the ions. The ion density peaks in the beam path, significantly enhancing the fusion rate along the interacting beams.

5. Proposed Initial Use in Low Power Research Reactors

The first use of IEC driven systems could well be for application to low-power research reactors. In this case, a lower source strength is required, and present experimental IEC devices are very close to meeting the desired goal. This concept is illustrated by some approximate calculations for a representative system.

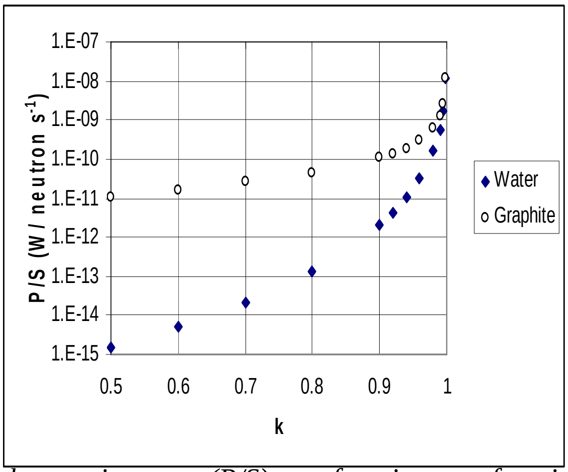

Figure 4 Power level per unit source (P/S) as a function as a function of k_∞ for two different moderators

Figure 4 presents the power obtained per unit source as a function of the multiplication factor k_∞. The system is assumed to be a cylindrical homogeneous reactor, fueled by uranium dioxide. Results for two different moderators, graphite and water, are presented. The fuel enrichment is adjusted to give the desired value of k_∞, maintaining the fraction of core volume occupied by the fuel fixed at 5%. From the figure, it can be observed that the graphite-moderated system can deliver 1 kW of power with a source of 10^{12} neutrons/sec when the multiplication factor of the reactor is 0.99, far from critical. Specifications for that system are summarized in Table 1.

Table 1: Parameters for a 1 kW graphite- moderated sub-critical system.

Fuel	UO_2 (0.5% U-235)
Moderator material	Graphite
Moderator volume fraction	95%
Multiplication factor	0.99
Radius (cm); Height (cm)	30; 50
Source strength (neutrons/s)	$1\text{x}10^{12}$
Power (kW)	1.2

In summary, while these calculations are quite approximate, this study provides a target reference design for a 1-kW IEC driven graphite moderated research reactor. As discussed earlier such a reactor appears to be quite attractive from a cost and safety point of view. Also, since existing experimental IEC devices have already achieved ~10^{11} DT n/s equivalent, the improvement required in this technology to achieve the target of 10^{12} n/s to drive the system outlined in Table 1 appears to be feasible in the near term. This is consistent with the source levels used in existing research reactors such as Garching II where sub-critical operation is based on a Cf-252 neutron source with $4\text{x}10^9$ neutrons/sec.

6. IEC Configuration for the Sub-critical Reactor Design

The IEC driven-reactor system would be designed to ensure safety against criticality and loss-of-cooling accidents as is done in the conventional accelerator-target designs. Some important differences exist, however, in the method used to safeguard against hypothetical beam power and reactivity increase accidents. In accelerator designs, a passive beam "shut-off" device is incorporated using a combination of thermocouple readings and a melt-rupture disk in the side-wall of the beam guide tube [17]. The IEC would use a simple temperature sensitive fuse in the in-core electrical circuit to shut down the high-voltage needed to maintain neutron generation. A melt rupture disk on the IEC wall could be added to spoil the IEC vacuum.

To illustrate the IEC system, a rough conceptual design for a 1000 MWe plant has been developed. The reactor core employs distributed IEC units as shown in Figs 5a and 5b.

Figure 5a. Vertical cross-section of the core showing cylindrical IEC modules (Dark vertical lines), Figure 5b. Cross-section view of the reactor core showing the IEC modules (cross-hatched channels)

In this design, cylindrical IEC units occupy seven fuel channels and are stacked such that 15 units stacked in each channel. Although a variety of arrays are conceivable, this particular configuration was selected to optimize neutron profiles in both the radial and vertical directions across the core. This "distributed source" design is to be contrasted to a accelerator-driven reactor where the center of the core is allocated to the spallation target (STET). In contrast, waste heat from the IEC is deposited on the large area hollow electrodes and removed through the normal coolant flow around the fuel channels.

The conceptual 1000-MWe reactor is designed with a k_{eff} < 0.99 such requiring ~10^{15} n/s per IEC module. This source rate is to be compared to the present experimental values of ~10^{11} D-T n/s from the pulsed C-device (the D-T "equivalent" yield based on measured D-D rates). While the driven reactor requirement is four orders of magnitude larger, there does not appear to be a fundamental block for such a scale-up in source strength [17-18]. Since IEC scaling involves velocity space scattering losses (vs. cross-field diffusion as in other magnetic confinement devices), increasing the yield does not require a significant increase in unit size. Instead, higher beam currents and improved ion recirculation are the key physics issues. Other crucial issues involve technology concerns such as incorporation of other high-voltage stand-offs that are "radiation hardened" against the high nuclear radiation levels encountered in the nuclear core. Fortunately, many of these issues can be studied using small unit, allowing a low cost, time effective R&D program.

7. Conclusions

An alternative to the standard driven reactor accelerator-spallation target design is proposed which employs IEC neutron sources which can be in a central location or distributed across a number of fuel channels. Such a modular design has distinct advantages in reduced driver costs, plus added flexibility in optimizing neutron flux profiles in the core. The basic physics for the IEC has been demonstrated in small-scale laboratory experiments, but a scale-up in source strength is required for ultimate power reactors.

However, the IEC source strength is already near the level required for low power research reactors or for student subcritical laboratory devices. This application would be advantageous since the safety advantages of these reactors should enable a next generation of research reactors to be constructed quickly, meeting the educational and research needs facing us as there is a rebirth of interest in nuclear power.

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